CS380: Computer Graphics
Ray Tracing

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(윤성의)

Course URL:
http://sglab.kaist.ac.kr/~sungeui/CG/

Class Objectives

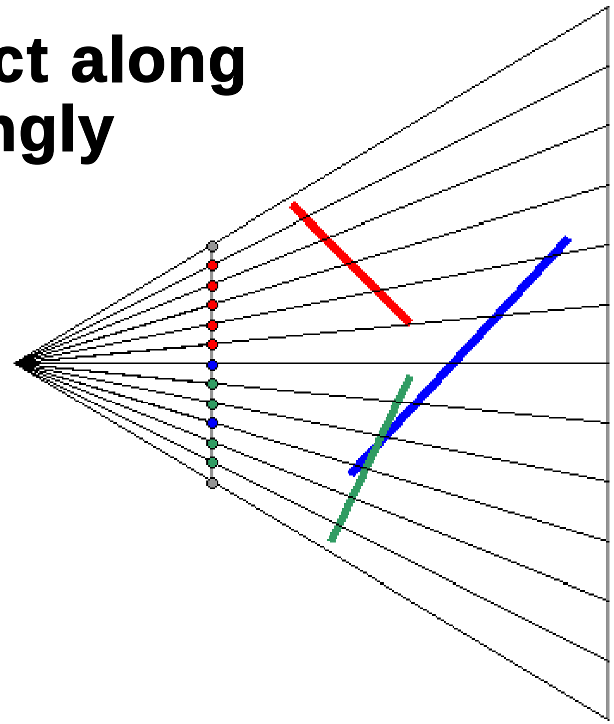
- Understand overall algorithm of recursive ray tracing
  - Ray generations
  - Intersection tests
  - Basic sampling methods

Various Visibility Algorithm

- Z-buffer
- Scan-line algorithm
- Ray casting, etc.

Ray Casting

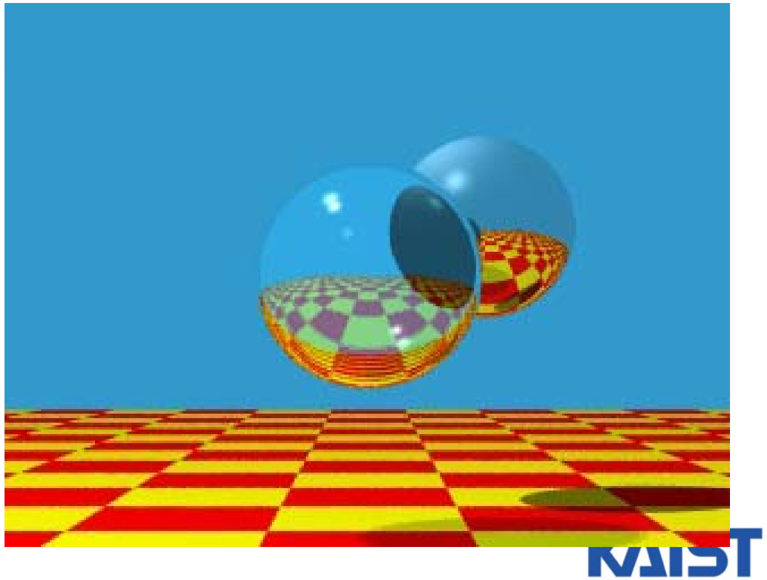
- For each pixel, find closest object along the ray and shade pixel accordingly



- Advantages
  - Conceptually simple
  - Can take advantage of spatial coherence in scene
  - Can be extended to handle global illumination effects
- Disadvantages
  - Renderer must have access to entire retained model
  - Hard to map to special-purpose hardware

Recursive Ray Casting

- Ray casting generally dismissed early on because of aforementioned problems
- Gained popularity in when Turner Whitted (1980) showed this image
  - *Show recursive* ray casting could be used for global illumination effects

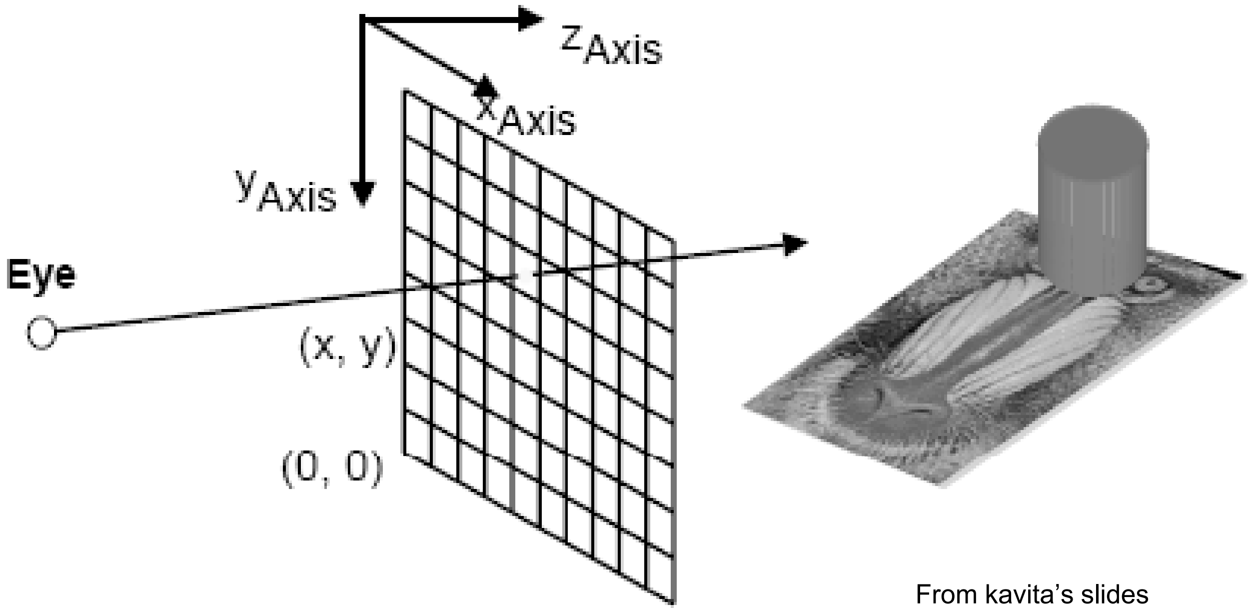


Ray Casting and Ray Tracing

- Trace rays from eye into scene
  - Backward ray tracing
- Ray casting used to compute visibility at the eye
- Perform ray tracing for arbitrary rays needed for shading
  - Reflections
  - Refraction and transparency
  - Shadows

Basic Algorithms of Ray Tracing

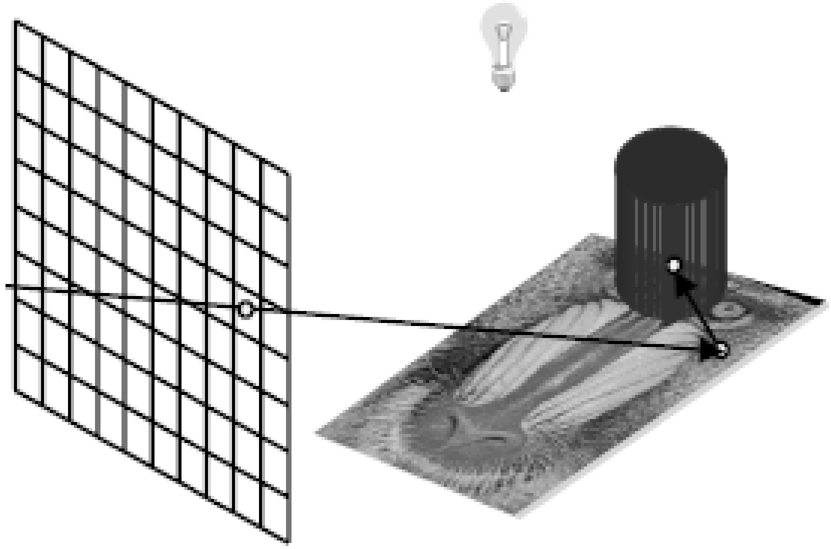
- **Rays are cast from the eye point through each pixel in the image**

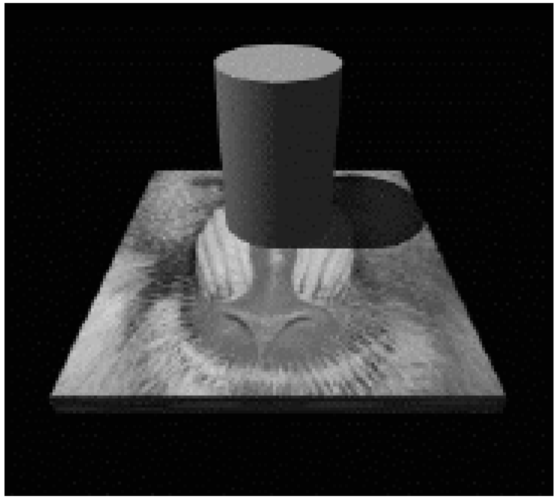


From kavita's slides

Shadows

- Cast ray from the intersection point to each light source
  - Shadow rays





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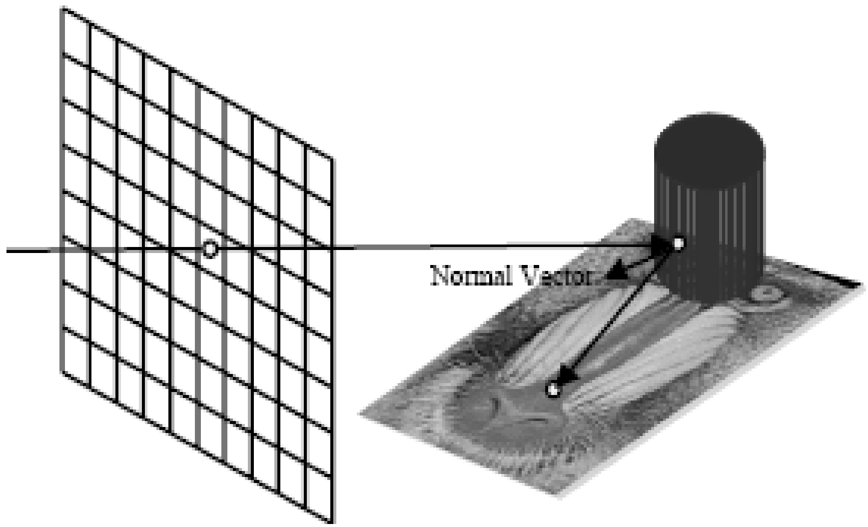
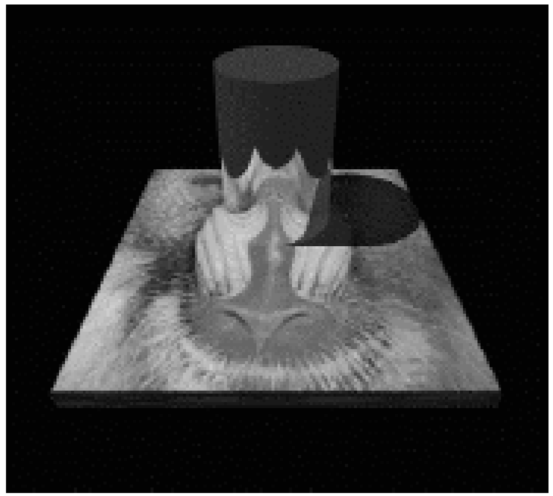
Reflections

- **If object specular, cast secondary reflected rays**





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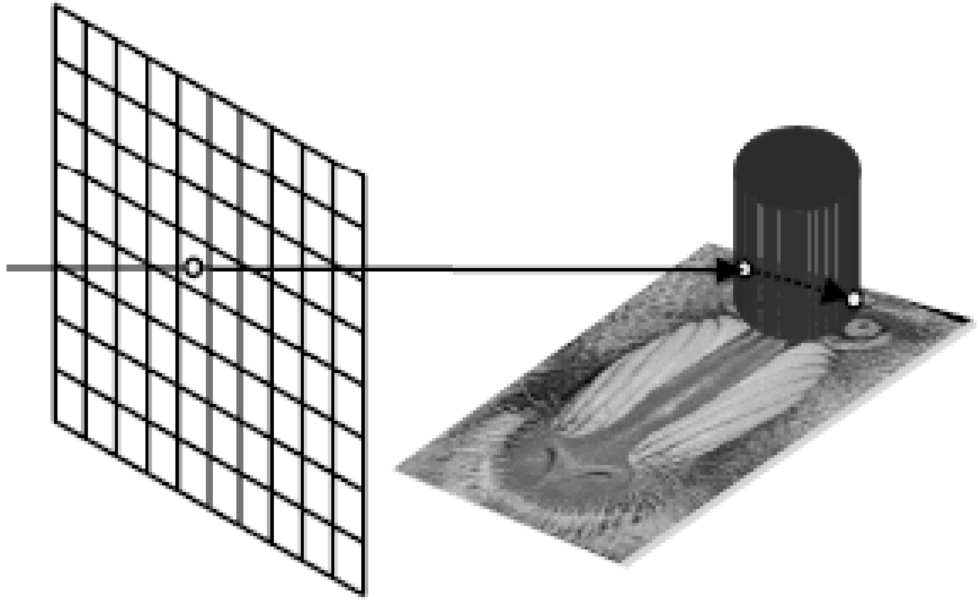
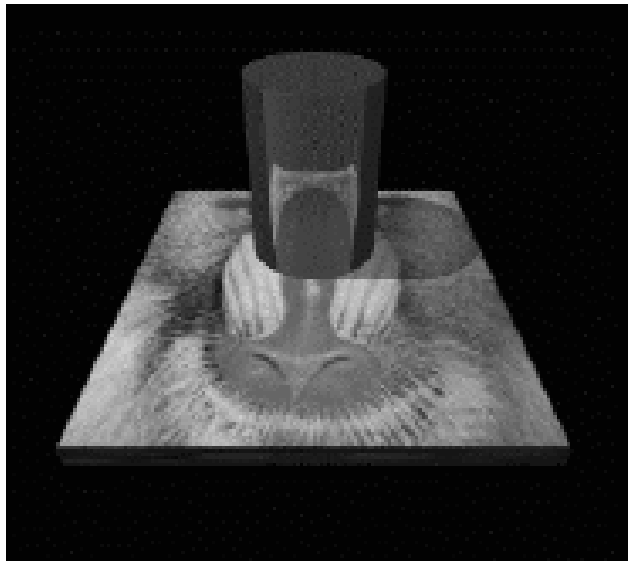
Refractions

- **If object tranparent, cast secondary refracted rays**





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An Improved Illumination Model [Whitted 80]

- **Phong model**

$$I_r = \sum_{j=1}^{numLights} (k_a^j I_a^j + k_d^j I_d^j (\hat{N} \bullet \hat{L}_j) + k_s^j I_s^j (\hat{V} \bullet \hat{R})^{n_s})$$

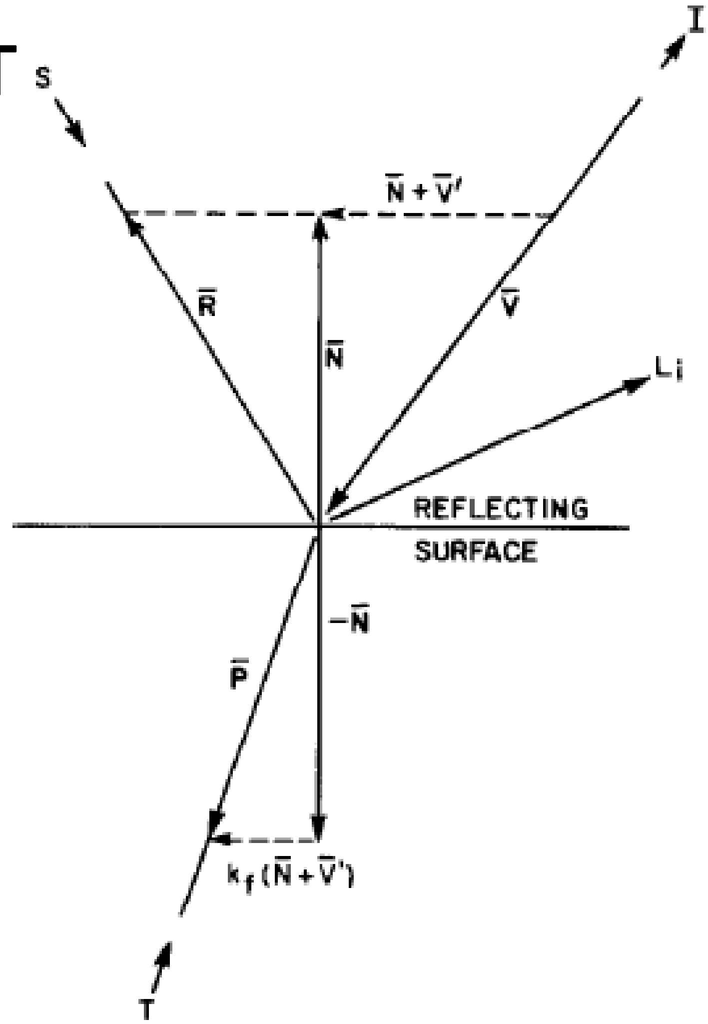
- **Whitted model**

$$I_r = \sum_{j=1}^{\mathbf{num\_Visible\_Lights}} (k_a^j I_a^j + k_d^j I_d^j (\hat{N} \bullet \hat{L}_j)) + k_s S + k_t T$$

  - **S and T are intensity of light from reflection and transmission rays**
  - **Ks and Kt are specular and transmission coefficient**

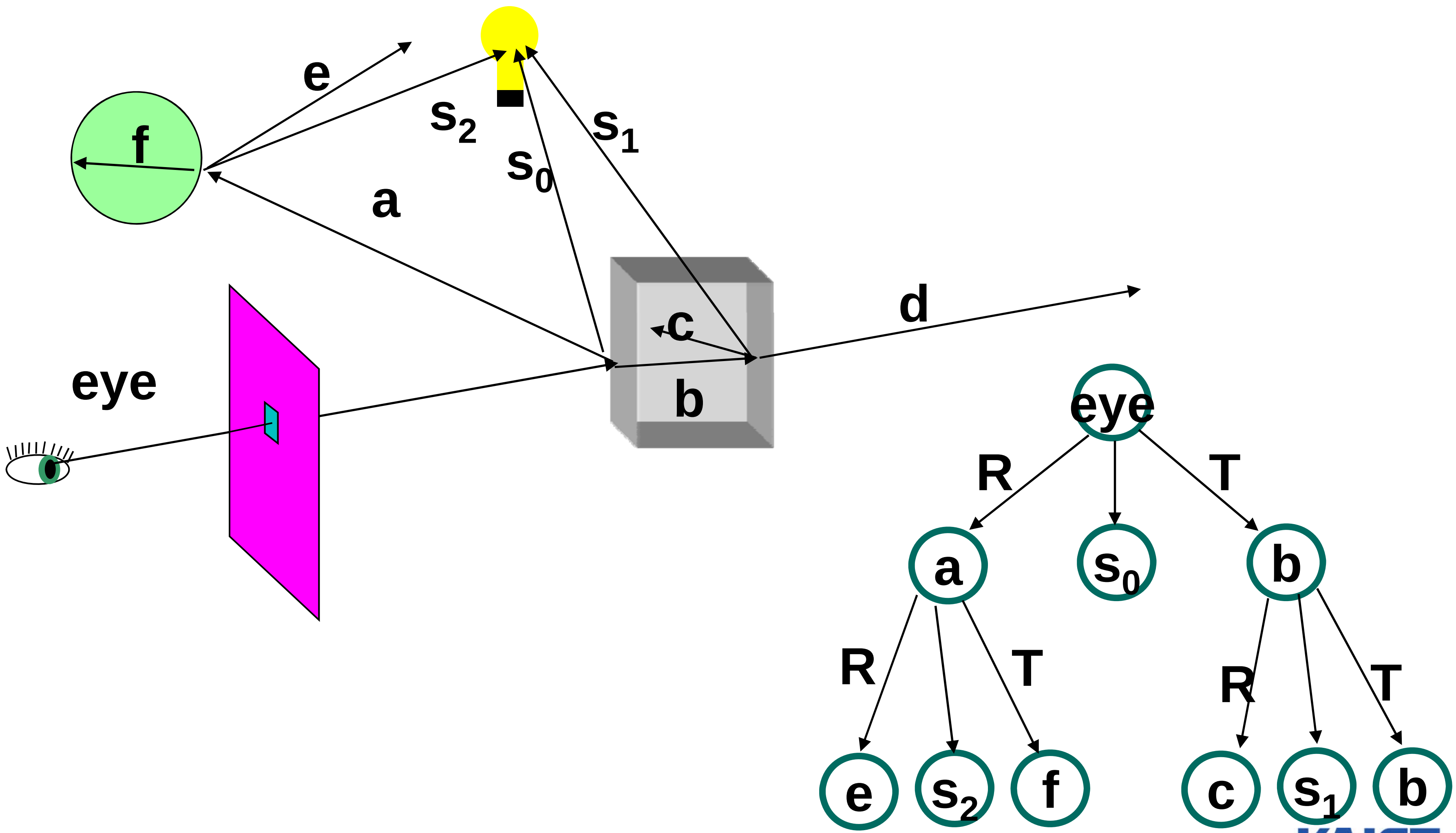
An Improved Illumination Model [Whitted 80]

$$I_r = \sum_{j=1}^{numLights} (k_a^j I_a^j + k_d^j I_d^j (\hat{N} \bullet \hat{L}_j)) + k_s S + k_t T$$



Computing reflection and transmitted/refracted rays is based on Snell's law (refer to Chapter 9.6 and 9.7)

Ray Tree



Overall Algorithm of Ray Tracing

- Per each pixel, compute a ray, R

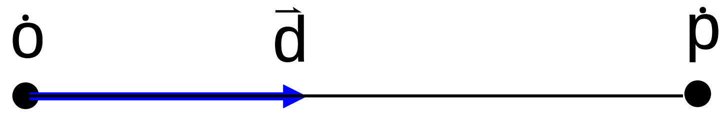
function RayTracing (R)

- Compute an intersection against objects
- If no hit,
  - Return the background color
- Otherwise,
  - Compute shading, c
  - General secondary ray, R'
  - Perform c' = RayTracing (R')
  - Return c+c'

Ray Representation

- **We need to compute the first surface hit along a ray**
  - **Represent ray with origin and direction**
  - **Compute intersections of objects with ray**
  - **Return closest object**

$$\dot{p}(t) = \dot{o} + t\vec{d}$$



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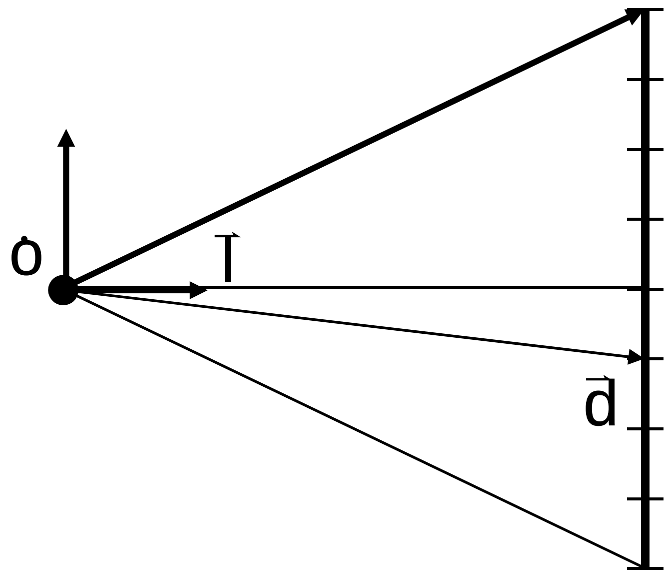
Generating Primary Rays



Generating Secondary Rays

- The origin is the intersection point p_0
- Direction depends on the type of ray
  - Shadow rays – use direction to the light source
  - Reflection rays – use incoming direction and normal to compute reflection direction
  - Transparency/refraction – use snell's law

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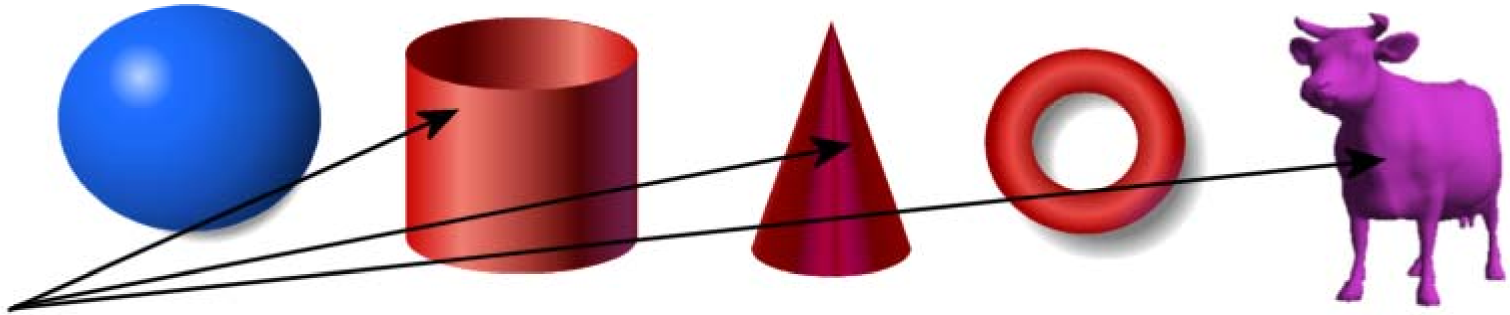
Intersection Tests

- Go through all of the objects in the scene to determine the one closest to the origin of



- Strategy: Solve of the intersection of the Ray with a mathematical description of the object

Simple Strategy

- **Parametric ray equation**
  - **Gives all points along the ray as a function of the parameter**

$$\dot{p}(t) = \dot{o} + t\vec{d}$$

- **Implicit surface equation**
  - **Describes all points on the surface as the zero set of a function**

$$f(\dot{p}) = 0$$

- **Substitute ray equation into surface function and solve for t**

$$f(\dot{o} + t\vec{d}) = 0$$

Ray-Plane Intersection

- **Implicit equation of a plane:**

$$\vec{n}\cdot\vec{p}-d=0$$

- **Substitute ray equation:**

$$\vec{n}\cdot(\vec{o}+t\vec{d})-d=0$$

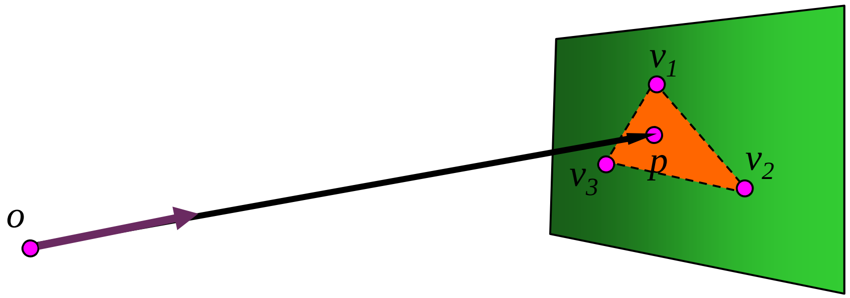
- **Solve for t:**

$$t(\vec{n}\cdot\vec{d})=d-\vec{n}\cdot\vec{o}$$

$$t=\frac{d-\vec{n}\cdot\vec{o}}{\vec{n}\cdot\vec{d}}$$

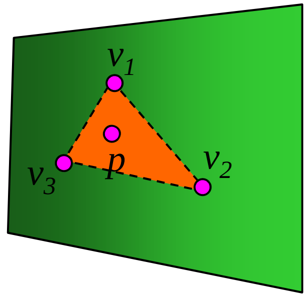
Generalizing to Triangles

- Find of the point of intersection on the plane containing the triangle
- Determine if the point is inside the triangle
  - Barycentric coordinate method
  - Many other methods

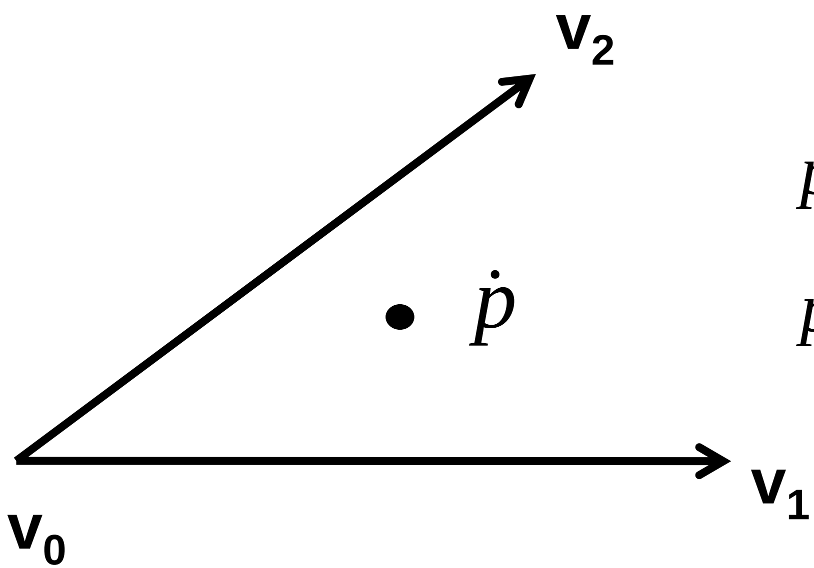


Barycentric Coordinates

- **Points in a triangle have positive barycentric coordinates:**



$$\dot{p} = \alpha \dot{v}_0 + \beta \dot{v}_1 + \gamma \dot{v}_2$$ **,where** $$\alpha + \beta + \gamma = 1$$



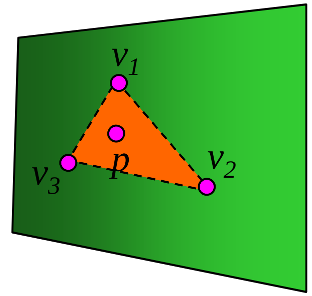
$$\dot{p} = \dot{v}_0 + \beta(\dot{v}_1 - \dot{v}_0) + \gamma(\dot{v}_2 - \dot{v}_0)$$

$$\dot{p} = (1 - \beta - \gamma)\dot{v}_0 + \beta \dot{v}_1 + \gamma \dot{v}_2$$

Barycentric Coordinates

- **Points in a triangle have positive barycentric coordinates:**

$$\dot{p} = \alpha \dot{v}_0 + \beta \dot{v}_1 + \gamma \dot{v}_2 \quad \text{,where } \alpha + \beta + \gamma = 1$$

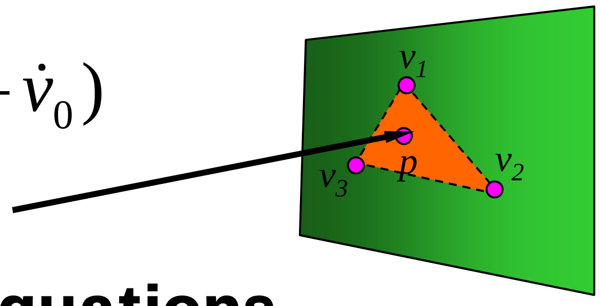


- **Benefits:**
  - **Barycentric coordinates can be used for interpolating vertex parameters (e.g., normals, colors, texture coordinates, etc)**

Ray-Triangle Intersection

- A point in a ray intersects with a triangle

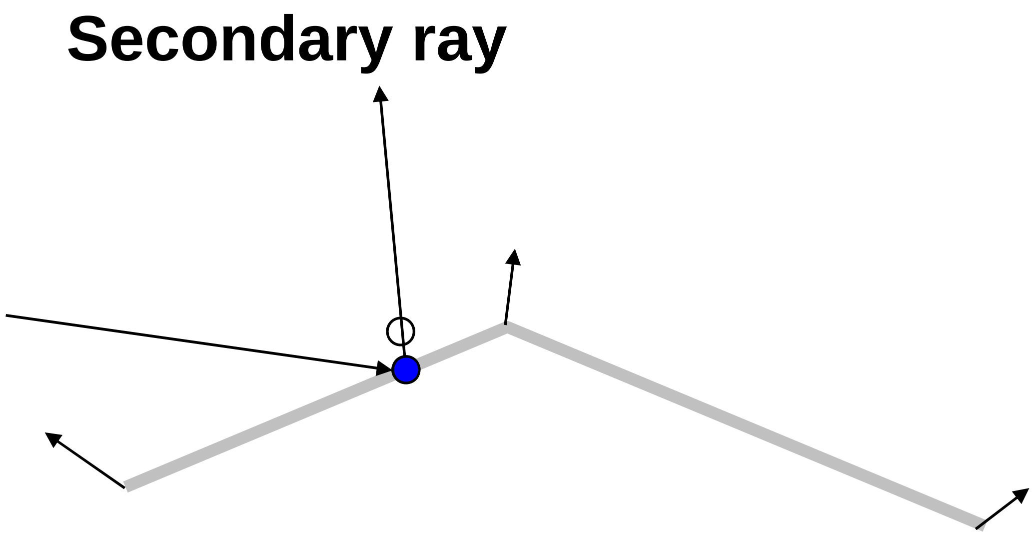
$$\dot{p}(t) = \dot{v}_0 + \beta(\dot{v}_1 - \dot{v}_0) + \gamma(\dot{v}_2 - \dot{v}_0)$$



  - Three unknowns, but three equations
  - Compute the point based on t
  - Then, check whether the point is on the triangle
  - Refer to Sec. 9.3.2 in the textbook for the detail equations

Robustness Issues

- **False self-intersections**
  - **One solution is to offset the origin of the ray from the surface when tracing secondary rays**



Pros and Cons of Ray Tracing

Advantages of Ray Tracing:

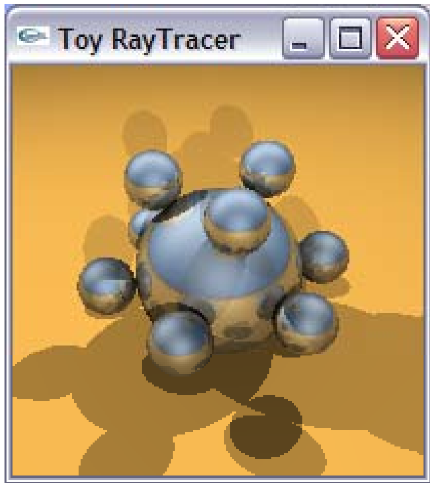
- Very simple design
- Improved realism over the graphics pipeline

Disadvantages:

- Very slow per pixel calculations
- Only approximates full global illumination
- Hard to accelerate with special-purpose H/W

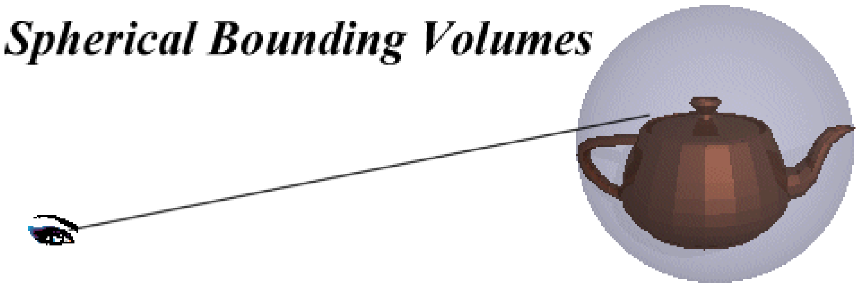
Acceleration Methods

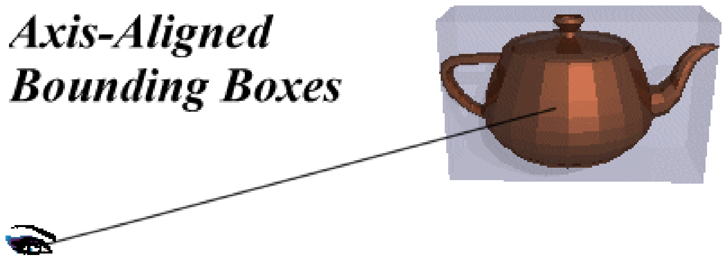
- Rendering time for a ray tracer depends on the number of ray intersection tests per pixel
  - The number of pixels X the number of primitives in the scene
- Early efforts focused on accelerating the ray-object intersection tests
- More advanced methods required to make ray tracing practical
  - Bounding volume hierarchies
  - Spatial subdivision



Bounding Volumes

- Enclose complex objects within a simple-to-intersect objects
  - If the ray does not intersect the simple object then its contents can be ignored
  - The likelihood that it will strike the object depends on how tightly the volume surrounds the object.

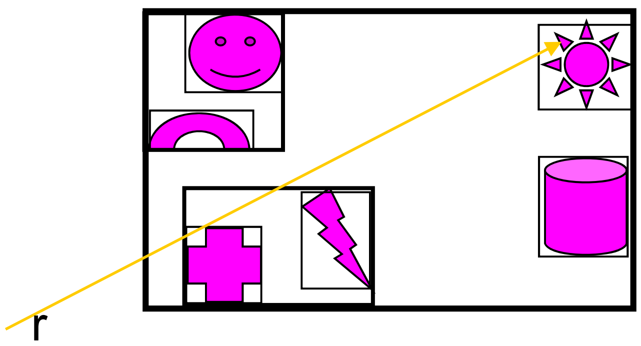


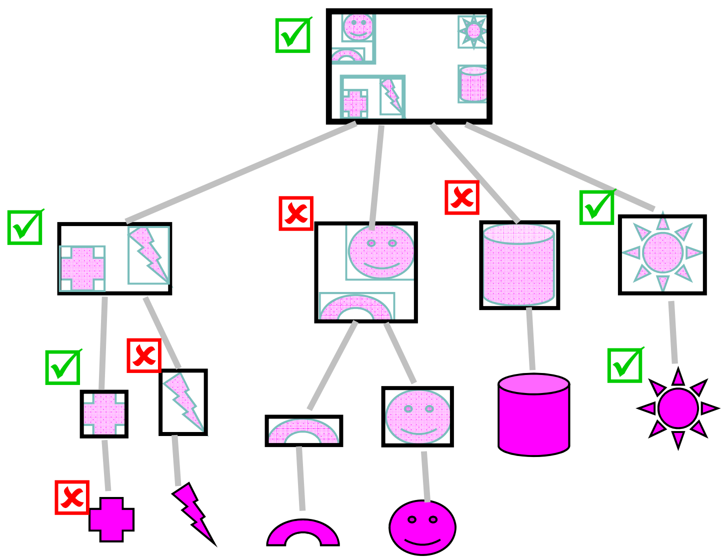


Potentially tighter fit,
but with higher computation

Hierarchical Bounding Volumes

- Organize bounding volumes as a tree
- Each ray starts with the root BV of the tree and traverses down through the tree

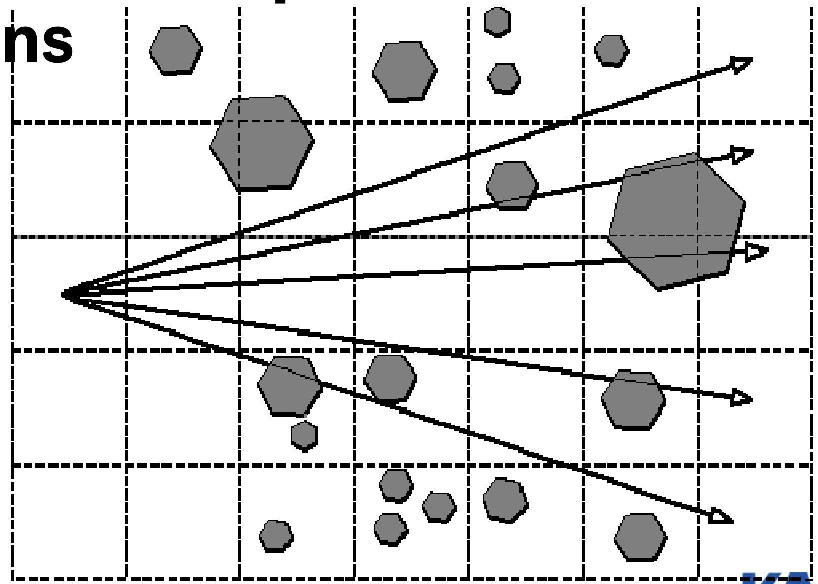




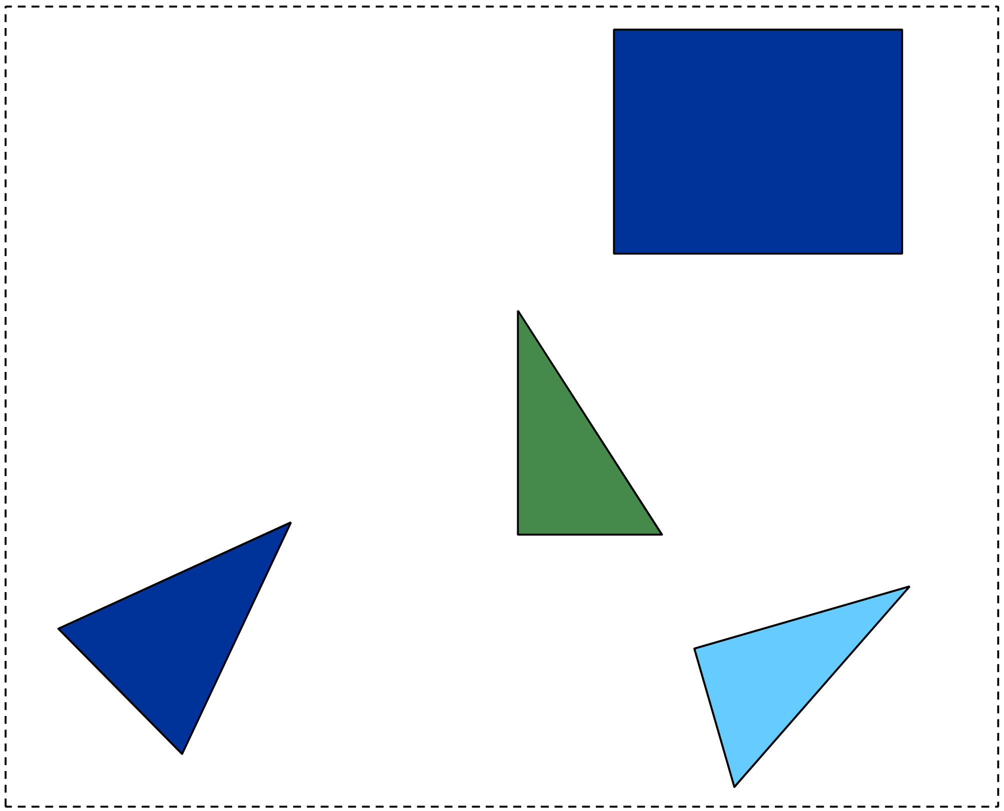
Spatial Subdivision

Idea: Divide space in to subregions

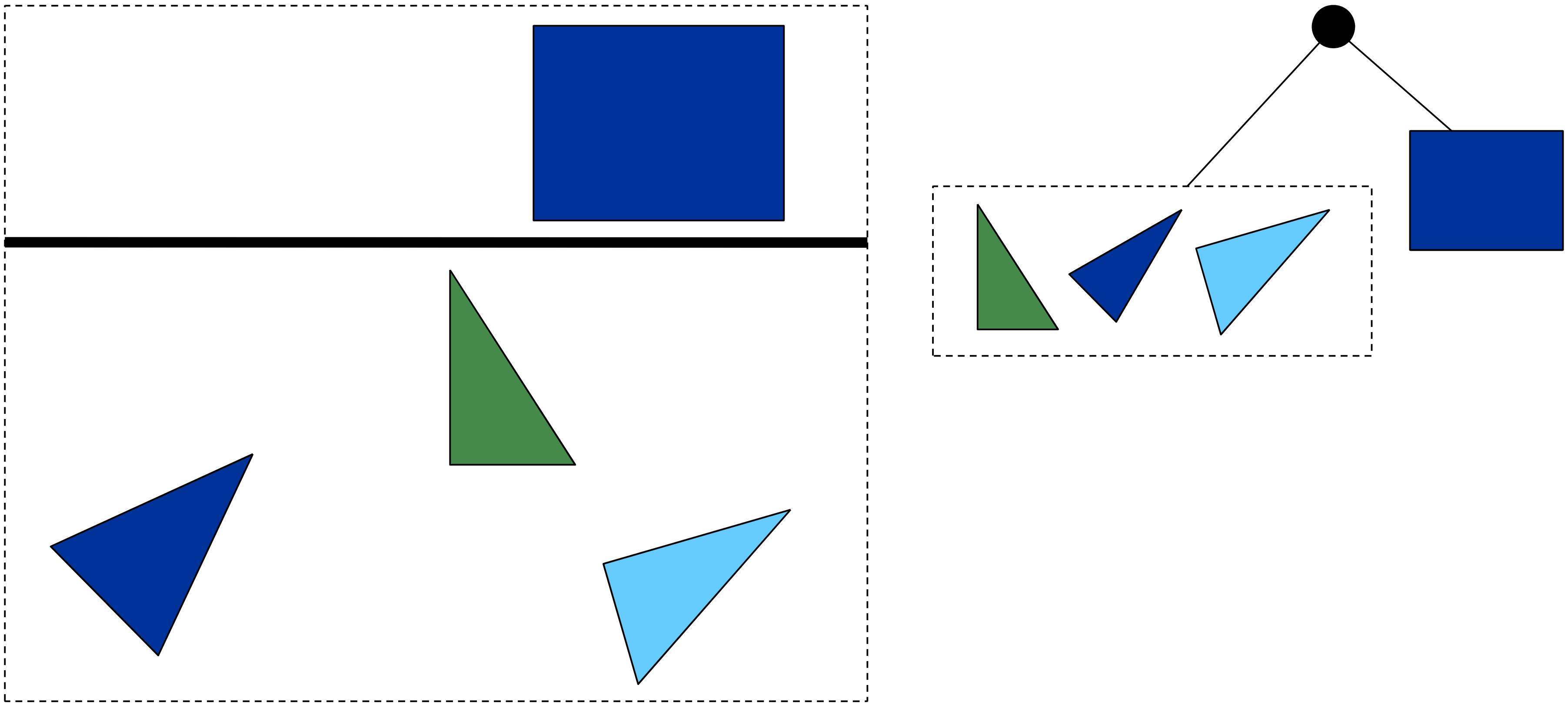
- Place objects within a subregion into a list
- Only traverse the lists of subregions that the ray passes through
- "Mailboxing" used to avoid multiple test with objects in multiple regions
- Many types
  - Regular grid
  - Octree
  - BSP tree
  - kd-tree



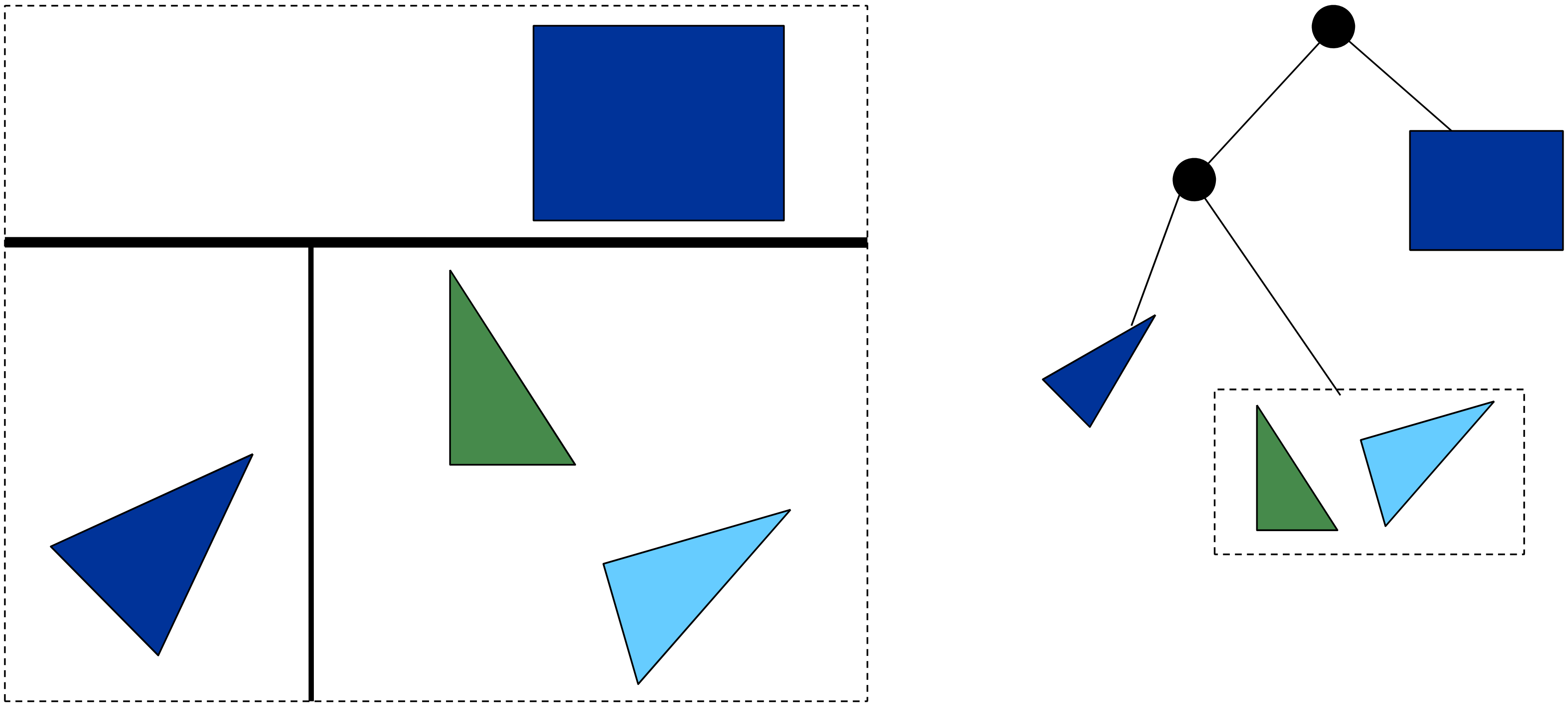
Kd-tree: Example



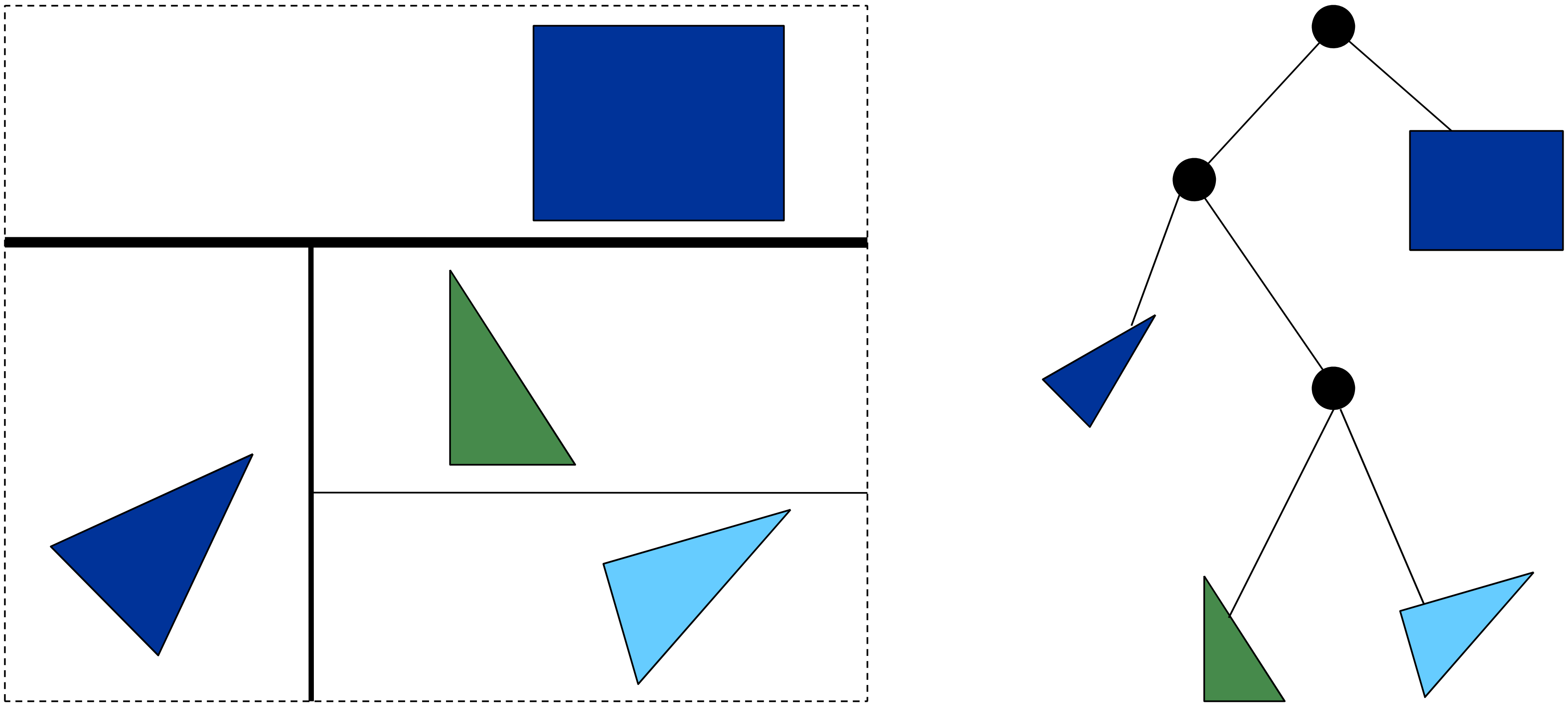
Kd-tree: Example



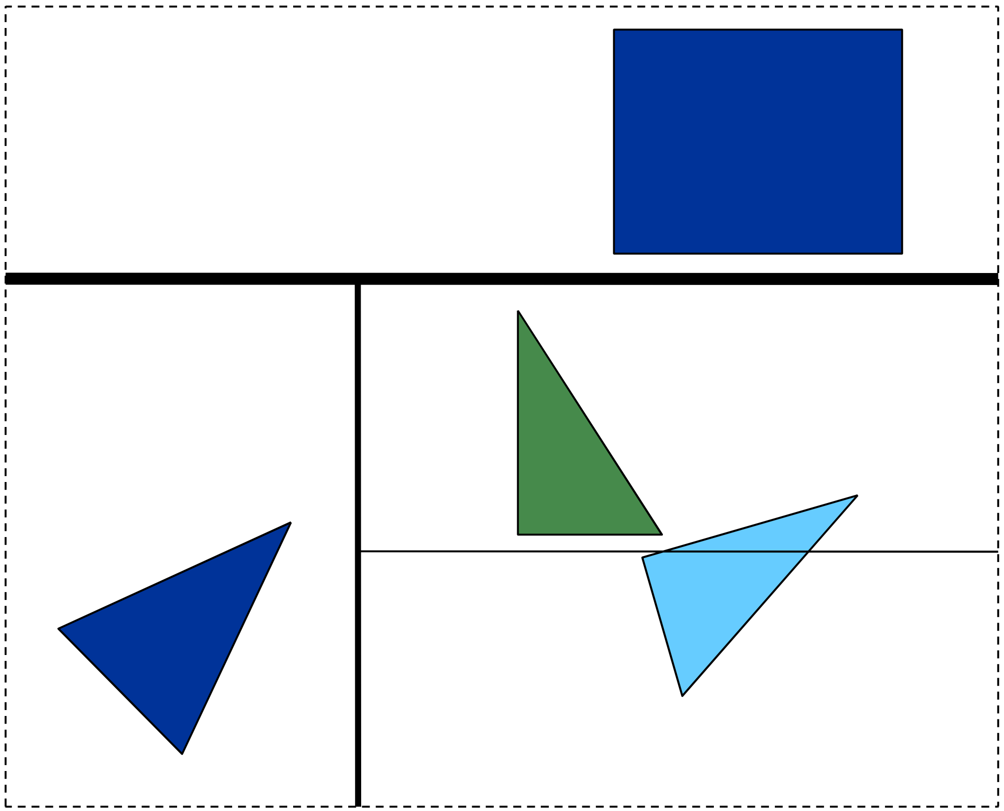
Kd-tree: Example



Example

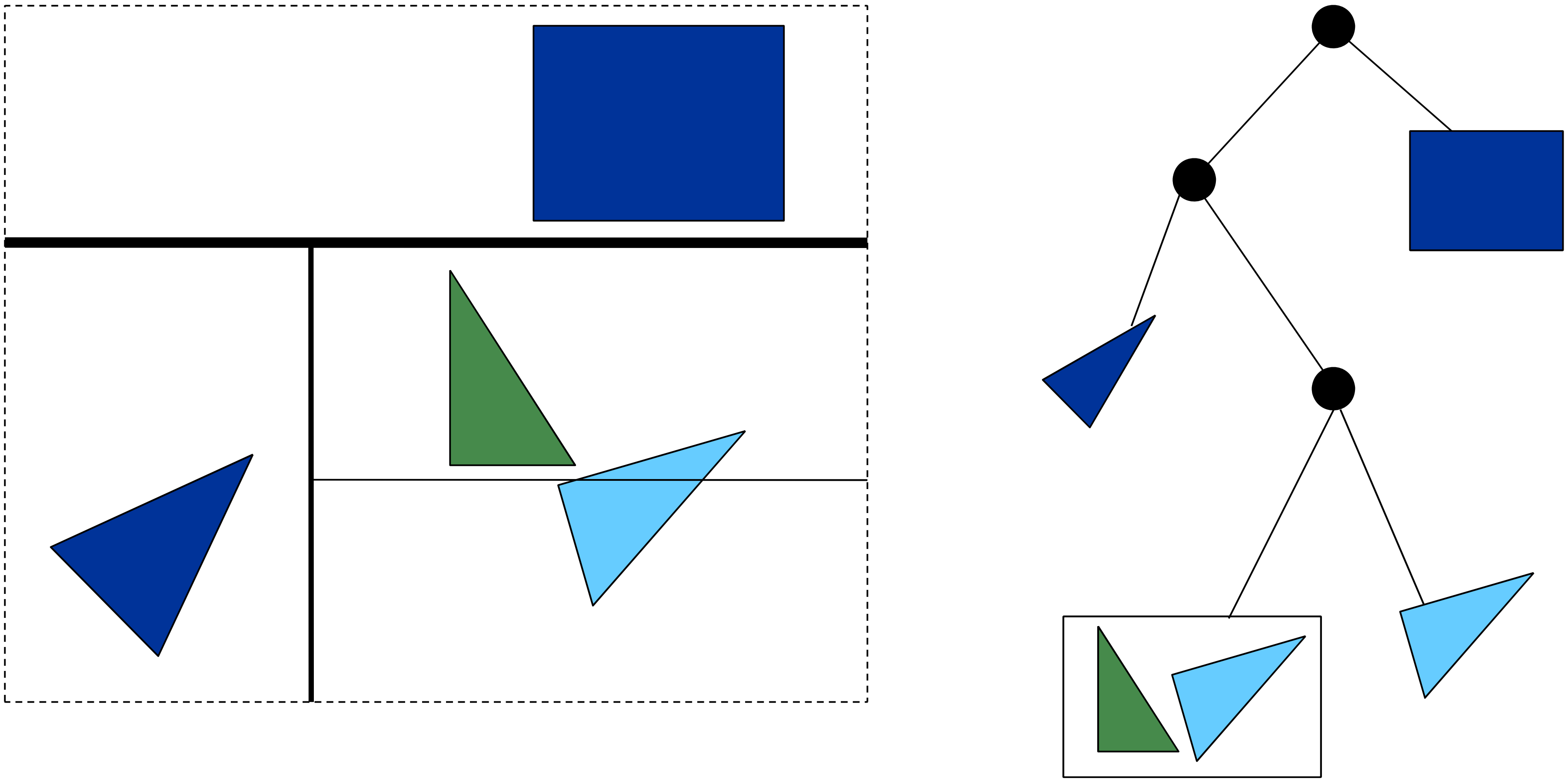


Kd-tree: Example



What about triangles overlapping the split?

Kd-tree: Example

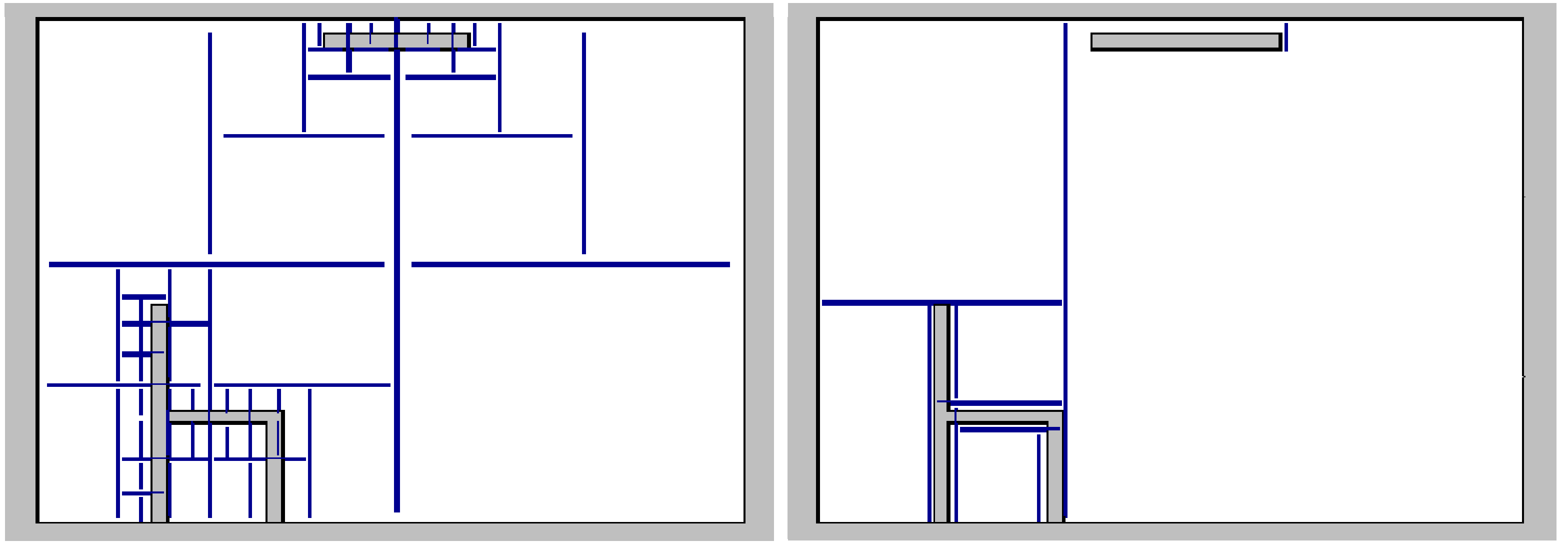


Split Planes

- **How to select axis & split plane?**
  - **Largest dimension, subdivide in middle**
  - **More advanced:**
    - **Surface area heuristic**

- **Makes large difference**
  - **50%-100% higher *overall* speed**

Median vs. SAH



(from [Wald04])

Ray Tracing with kd-tree

- Goal: find closest hit with scene
- Traverse tree front to back (starting from root)
- At each node:
  - If leaf: intersect with triangles
  - If inner: traverse deeper

Other Optimizations

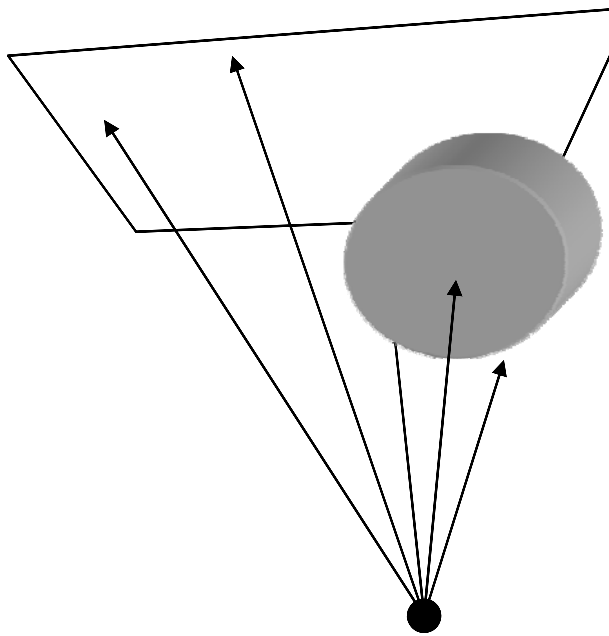
- Shadow cache
- Adaptive depth control
- Lazy geometry loading / creation

Distributed Ray Tracing [Cook et al. 84]

- Cook et al. realized that ray-tracing, when combined with randomized sampling, which they called “jittering”, could be adapted to address a wide range of rendering problems:

Soft Shadows

- Take many samples from area light source and take their average
  - Computes fractional visibility leading to penumbra

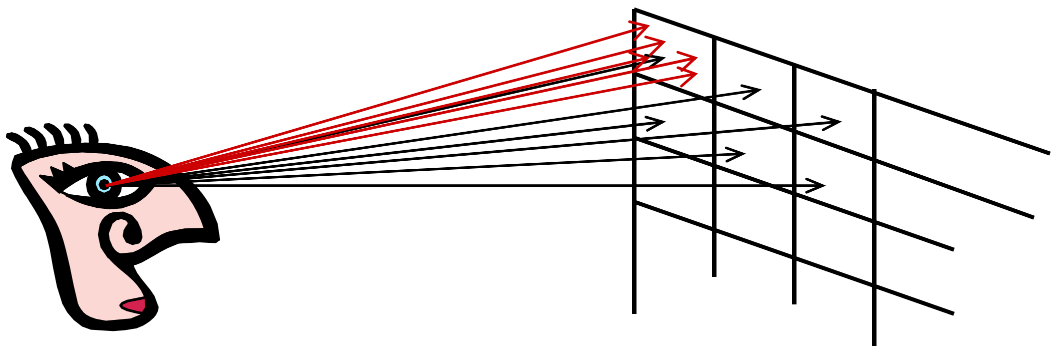


Antialiasing

- The need to sample is problematic because sampling leads to aliasing
- Solution 1: super-sampling
  - Increases sampling rate, but does not completely eliminate aliasing
  - Difficult to completely eliminate aliasing without prefiltering because the world is not band-limited

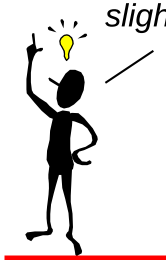
Antialiasing

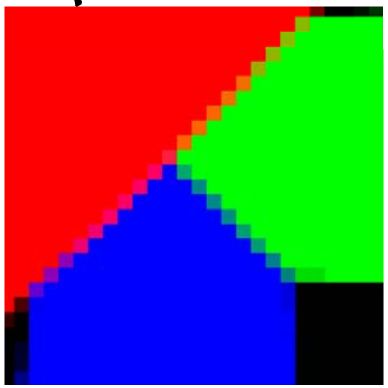
- **Solution 2: distribute the samples randomly**
  - **Converts the aliasing energy to noise which is less objectionable to the eye**



Instead of casting one ray per pixel, cast several sub- sampling.

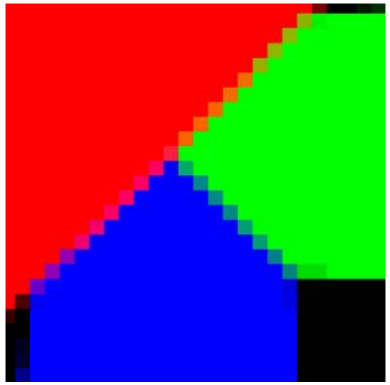
Instead of uniform sub-sampling, jitter the pixels slightly off the grid.

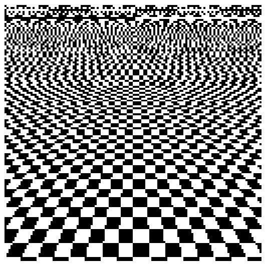


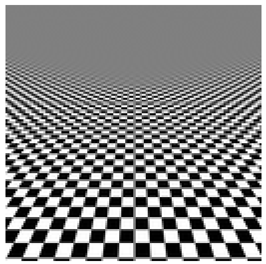


Jittering Results for Antialiasing

2x2
sub-sampling

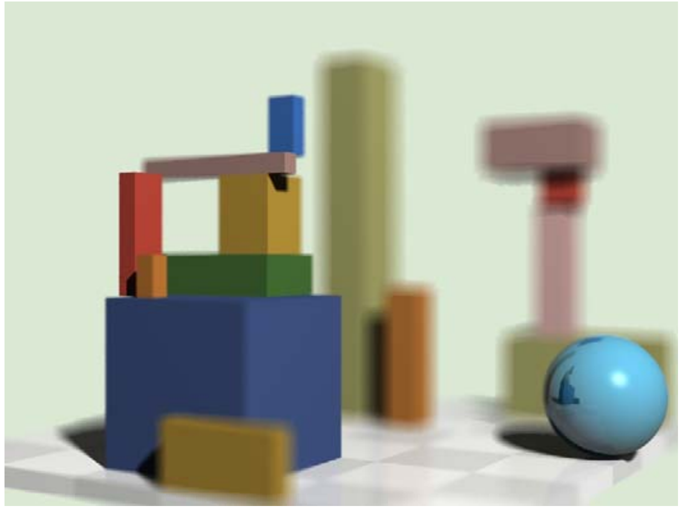




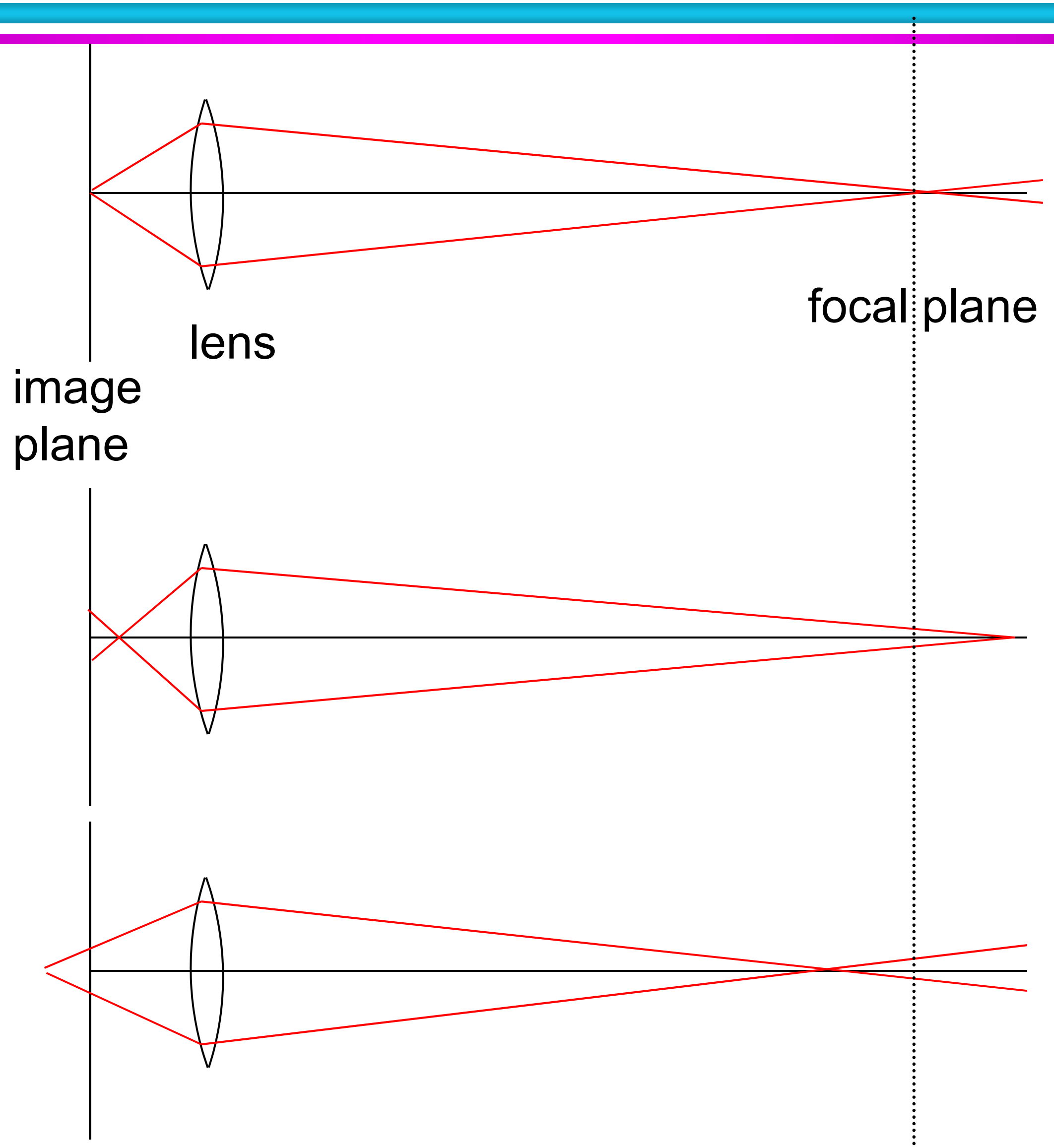


Depth-of-Field

- Rays don't have to all originate from a single point.
- Real cameras collects rays over an aperture
  - Can be modeled as a disk
  - Final image is blurred away from the focal plane
  - Gives rise to depth-of-field effects

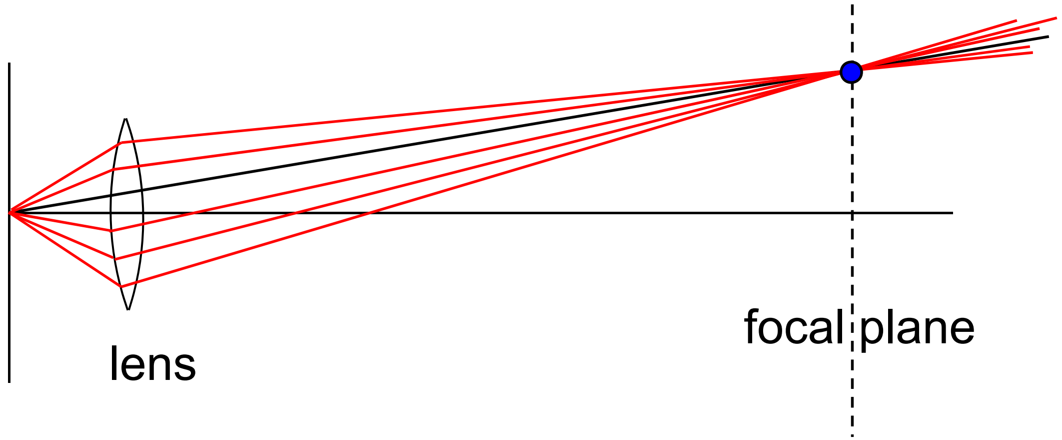


Depth of Field



Depth of Field

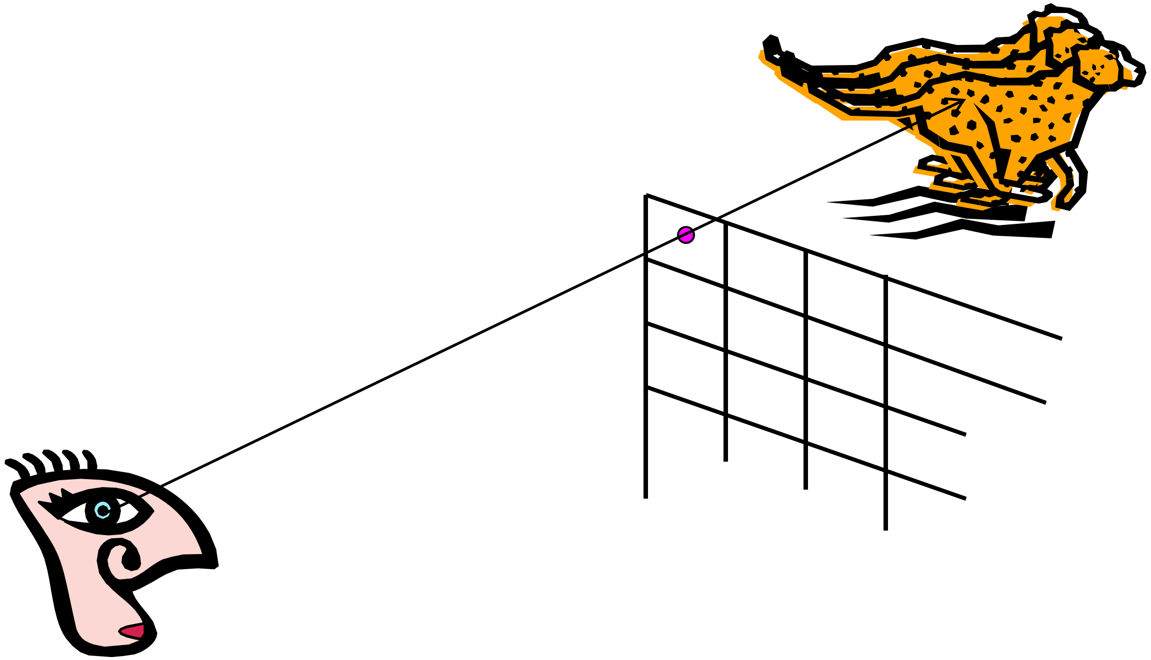
- Start with normal eye ray and find intersection with focal plane
- Choose jittered point on lens and trace line from lens point to focal point



Motion Blur

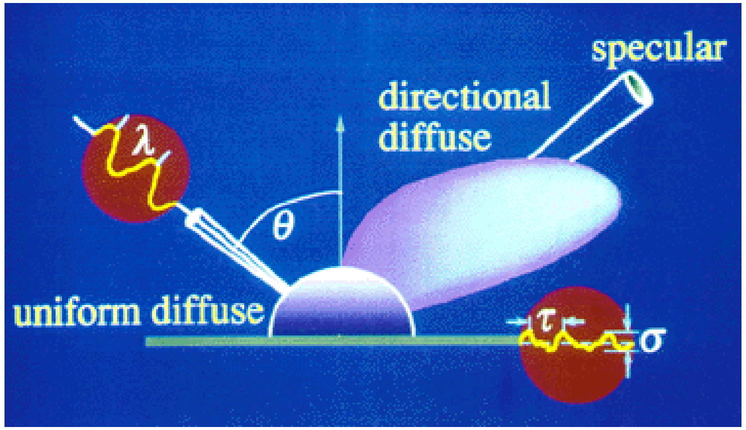
- Jitter samples through time
  - Simulate the finite interval that a shutter is open on a real camera

Motion Blur



Complex Interreflection

- Model true reflection behavior as described by a full BRDF
- Randomly sample rays over the hemisphere, weight them by their BRDF value, and average them together
  - This technique is called “Monte Carlo Integration”



CS680

- **Advanced Computer Graphics**
  - **Focus on rendering techniques that generate photo-realistic images**

- **CS580 at spring 2013**
  - **I'll teach high-quality rendering techniques**